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ASSESSMENT AND HANDLING OF CA CODE SELF-INTERFERENCE DURING WEAK GPS SIGNAL ACQUISITION (PREPRINT)

Y.T. Jade Morton, James B.Y. Tsui, David M. Lin, L.L. Liou, Mikel M. Miller, John Schamus, and Qihou Zhou

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This paper presents an analysis of GPS CA code self-interference, its impact on the acquisition of weak GPS signal when coexisting with strong GPS signals, and means to mitigate the interference to allow successful acquisition of the weak GPS signals using software GPS receivers. Current software GPS receivers are capable of acquiring and tracking satellite signals with C/N_0 as low as 24 dB, which is the sensitivity limit of a stand-alone GPS receiver. To achieve this level of sensitivity, there cannot be substantial interference from other satellites with strong signal levels. In practicality, however, the weak signals may coexist with much stronger signals from other satellites. This may happen when only a limited area of the sky is exposed to a receiver such as in the case of navigating in city canyon or under forest canopy. The presence of the strong signals may produce higher cross correlations between the strong signals and a weak signal, resulting in complete loss or false acquisition of weak signals which maybe necessary in helping to determine the user position.

Software algorithm are developed that can successfully remove the strong satellite signals from the GPS receiver input. The resulting net input signal can then be used to acquire the weak signals. Experiments using both simulation and simulator data show that with the removal of strong satellite signal from the input, it is possible to acquire weak satellite near the sensitivity limit.

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Assessment and Handling of CA Code Self-Interference during Weak GPS Signal Acquisition

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ABSTRACT

This paper presents an analysis of GPS CA code self-interference, its impact on the acquisition of weak GPS signal when coexisting with strong GPS signals, and means to mitigate the interference to allow successful acquisition of the weak GPS signals using software GPS receivers. Current software GPS receivers are capable of acquiring and tracking satellite signals with C/N_0 as low as 24 dB, which is the sensitivity limit of a stand-alone GPS receiver. To achieve this level of sensitivity, there cannot be substantial interference from other satellites with strong signal levels. In practicality, however, the weak signals may coexist with much stronger signals from other satellites. This may happen when only a limited area of the sky is exposed to a receiver such as in the case of navigating in city canyon or under forest canopy. The presence of the strong signals may produce higher cross correlations between the strong signals and a weak signal, resulting in complete loss or false acquisition of weak signals which maybe necessary in helping to determine the user position.

Software algorithm are developed that can successfully remove the strong satellite signals from the

GPS receiver input. The resulting net input signal can then be used to acquire the weak signals. Experiments using both simulation and simulator data show that with the removal of strong satellite signal from the input, it is possible to acquire weak satellite near the sensitivity limit.

1. INTRODUCTION

The GPS signal acquisition mechanism relies on the near orthogonal nature of the CA codes. When all satellite signals are of compatible strength, the autocorrelation peak of a CA code is about 24 dB above cross-correlation peaks between different CA codes, providing a wide dynamic range for signal acquisition. If a combination of strong and weak signals is present in the GPS receiver input, the cross correlation between the strong and weak signals may be compatible with or surpass the weak signal autocorrelation peak. As a result, weak satellite signals, which may be critical to the pseudo-range calculation under certain circumstances, may not be successfully acquired.

The impact of the cross-correlation between CA codes on GPS receiver performance has been the subject of several studies [1, 2]. Much of the previous studies focused on the effect of CA code cross correlation on pseudo range calculation errors. This paper presents an assessment on the impact of the cross-correlation between CA codes during weak signal acquisition stage and means to mitigate the self-interference in the input signal.

A typical ground-based GPS receiver in direct view of a GPS satellite can obtain a signal whose signal to noise ratio referenced to 1Hz (C/No) is in the range of 45 dB-Hz to 52 dB-Hz. This figure can be translated into a signal to nosie ratio of –18dB to –11dB referenced to the 2MHz bandwidth of the C/A code signal. The fundamental acquisition techniques used in current GPS receivers are described in Van Dierendonck (1996) and Ward (1996). Various software approaches have also been developed to acquire signals at this range (Tsui, 2000; Lin and Tsui, 2000). Several innovative approaches have been developed to acquire weaker signals. Akos et al. (2000) presented a stand-alone technique that uses up to 10 ms of coherent integration time to acquire signal with C/N_0 approaching down to 32 dB-Hz. To acquire signals with even lower power levels, aided acquisition techniques were used in the study presented by Akos et al. Tsui (to be published) reports a stand-alone software receiver that can acquire and track signals with C/N_0 as low as 24 dBW-Hz using a combination of coherent and incoherent integration techniques. This result cannot be achieved, however, if the weak signal coexist with other signals of much stronger signal to noise ratio.

Psiaki (2001) discussed a computationally intensive approach that can acquire signal with $C/N_0 = 21$ dB-Hz by using 4s of input data in stand-alone mode. He also studied the case in which a weak signal is mixed wth several much stronger signals. By using strong signal parameters obtained from tracking programs, he estimated the strong signal amplitudes, and reconstructed the strong signals. The reconstructed signals are then subtracted from the input. The resulting net signal is used for acquisition of the weak signal. Using this approach, he was able to acquire weak signal with $C/N_0 = 38$ dB by using 5 incoherent integrations of 10ms coherent integration blocks. He also showed that by canceling the strong signals from the input data, the probability to detect weak signals is increased while the false alarm rate is decreased, a very much desirable outcome in acqusition.

The concept of strong signal cancelation was originated from the CDMA (code division multiple access) communication systems. A CDMA system is an multiuser system in which all users interfere with each other. To detect a signal from a specific user, it is essential to develop techniques to mitigate interference from other user's signals. The so-called successive interference cancelation (SIC) technique detects and cancels each interference signal in a serial manner, starting with the signal of the strongest power in the input (Hallen A., 1995).

Madhani et al. (2003) applied the SIC technique to the near-far problem encountered by a GPS system augmented by ground-based pseudolites. The relatively short distance between a pseudolite and a receiver causes large variations of pseudolite signal power levels at a receiver input. A pseudolite signal may easily overwhlem a nominal satellite signal when a receiver is in close prosimity of the pseudolite. To acquire satellite signal, Madhani et al. performed successive acquisition and cancelation of the strong pseudolite signals from the receiver input. The nominal satellite signals are acquired after all strong pseudolites are removed from the input. Their implementation worked when the pseudolite signal is 30 to 40 dB above the nominal satellite signal level. With such strong signal power, it is relatively easy to obtain accurate signal parameters for the pseudolite signal reconstruction and cancelation.

To effectively cancel nominal satellite signal from a satellite input so that a weak signal at the sensitivity limit level can be acquired is a more challenging task. If the nominal satellite signals are reconstructed inaccurately, the residue errors from the cancelation may increase the noise floor or introduce additional interference, making weak signal acquisition even harder to do. To acquire weak signals at the sensitivity level, it takes extended integration time. It is therefore necessary to maintain accurate reconstruction of the nominal satellite signals during the extented integration time to guarantee the minimum error residue from the cancelation. This can be a challenge for hardware implementations.

In this study, software approaches were used to acquire and track nominal signals (we will refer to these signals as strong signals in the remaining text of this paper). The strong signal parameters obtained from the software tracking program are used to form a matrix that represents an interference subspace. Projection of the input signal on to this subspace provides the reconstructed strong signal components. Subtracting the projection from the input gives net weak signal, noise, and residue errors from the strong signal cancelation. To minimize the residue error, the tracking program output is updated every 10 ms, and projection and strong signal cancelation is also performed for each 10 ms blocks of inputs. The net results from these 10 ms blocks of data are then put back together for weak signal acquisition.

A recently developed weak signal acquisition algorithm at AFRL is used to acquire the weak signals following the removal of the strong signals. This weak signal acquisition algorithm has successfully acquired weak signals with C/N_0 as low as 24dB using 200 ms of input data without extended computation time. Both simulation and hardware-based GPS simulator data were used to study testify the effectiveness of the self-interference removal.

Figure 1 show the general procedure used to mitigate the CA code self-interference and weak signal acquisition in this study.

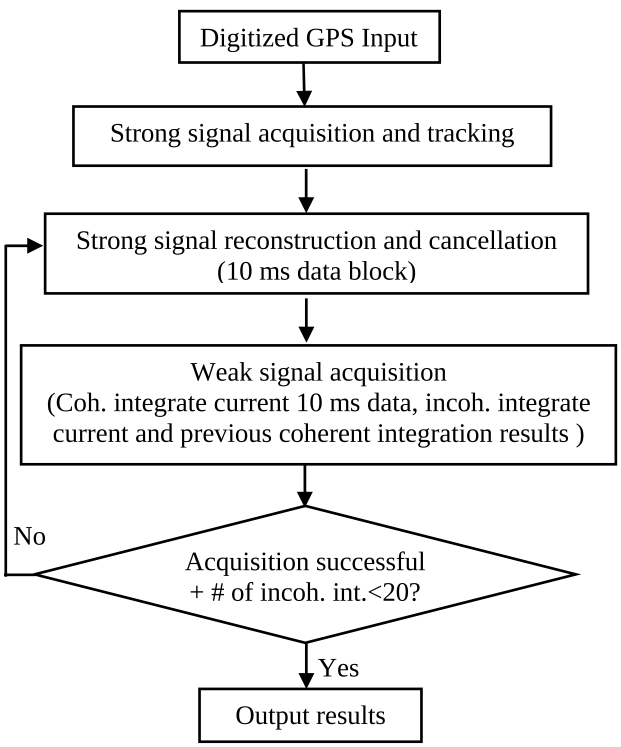

Fig.1. CA code removal and weak signal acquisition procedure

To gain quantitative measure of the effect CA code self-interference on weak signal acquisition, theoretical analysis and simulation studies were carried out. In the analysis, cross-correlations between CA codes are treated as additional noise during weak signal acquisition. Our analysis shows that the equivalent noise generated by the cross-correlation may significantly degrade the effective signal to noise ratio of a weak signal during its acquisition process. The amount of degradation depends on the input signal to noise ratio of the strong signal and of the weak signal, as well as the specific acquisition algorithm. For example, using the weak signal acquisition algorithm lately developed, a weak input signal with C/N_0 = 33dB may be degraded by up to 7 dB, if it coexists with a strong signal with C/N_0 = 49dB. The analysis is further confirmed by performing software-based acquisitions of simulation data.

Section 2 of the paper will present our analysis of the cross-correlation between various levels of GPS satellite signals and its impact on the effective weak signal to noise ratio. The self-interference cancellation procedure will be described in Section 3. Section 4 discusses a recent software receiver algorithm developed for weak signal acquisition at the AFRL, Wright Patterson Air Force Base. Section 5 presents the simulation and simulator data testing results, conclusions from this study.

2. CA CODE CROSS CORRELATION ANALYSIS

One way to gain an insight into the impact of strong-weak signal interference on weak signal acquisition is to examine the equivalent signal power associated with the average cross-correlation between a strong and a weak signal. Assuming a GPS input signal y consists of a strong satellite signal s, a weak satellite signal w, and noise n:

$$y = s + w + n \tag{1}$$

The strong signal and the weak signal's signal to noise ratios at the receiver input (assuming 2 MHz bandwidth) are:

$$SNR_S = 10\log\frac{P_S}{N} \tag{2}$$

$$SNR_W = 10\log\frac{P_W}{N} \tag{3}$$

Where,

N: noise power
P_S: Strong signal power
P_W: Weak signal power

Ignoring the details of coherent and incoherent integration, a weak signal acquisition procedure is based on the correlation calculation:

$$CA_w \otimes (s + w + n)$$

Where, CA_w is the weak signal CA code. Here, the most significant contribution in the correlation is $CA_w \otimes s$. If we ignore the impact of the carrier signal for the time being and only consider the presence of the CA code, then

$$s = a_s CA_s \tag{4}$$

$$P_s = a_s^{\;2} \tag{5}$$

Where, a_s is the strong signal amplitude.

The cross correlation between the strong and the weak signal's CA code is of random nature and will contribute to the total noise of the overall signal. The equivalent noise power of the cross correlation can be computed as following:

$$N_c = E[(CA_s \otimes s)^2] = a_s^2 E[(CA_s \otimes CA_w)^2] = P_s C \tag{6}$$

Here, we denoted the average cross correlation power between the two GPS satellite CA codes as a constant C:

$$C = E[(CA_s \otimes CA_w)^2] \tag{7}$$

The constant C can be calculated for any two sets of CA codes. Using a sampling rate of 5MHz, we obtained the average cross correlation power of two CA codes to be: C=7.0645x10^{-4}.

N_c, the equivalent noise power resulting from the cross correlations, coupled with the process gain (G) of the weak signal acquisition procedure results in a modified signal to noise ratio for the weak signal:

$$SNR_W^{'} = 10\log\frac{P_w}{N_c + N/G} \tag{8}$$

Substitute (5) and (3) into (8),

$$SNR_W^{'} = SNR_W + G_{dB} - 10\log(CG10^{\frac{SNR_S}{10}} + 1) \tag{9}$$

Where, G is the acquisition processing gain in ratio while G_{dB} is the gain in dB.

The goal of acquisition is to provide sufficient processing gain to a signal so that it can have a signal to noise ratio of 14 dB (according to the conventional radar performance evaluation criteria (Barton, 1988)). For a weak signal whose SNR is -39 dB at the receiver input (corresponding to C/N_0 =24 dB), this requirement indicates that a total of 53 dB processing gain is necessary. For this reason, we will use the following parameters in our calculation:

G_{dB} = 53 dB; G = 200000;

With the value G, G_{dB}, and C known, we can calculate the effective processed weak signal SNR ($SNR_W^{'}$) as a function of the input weak signal SNR (SNR_W) for a given strong signal SNR (SNR_S). We used the process gain of 53 dB and cross correlation noise of 7.0645x10^{-4} in the calculation. Figure 2 shows the relationship between the weak signal input signal to noise ratio and processed signal to noise ratio for different strong signal levels. For example, if a strong signal SNR is -13 dB, then a weak signal with SNR=-39 dB will have a processed SNR of about 5 dB. This level is below the level of 14 dB defined by the detection criteria. Therefore, it cannot be acquired. The red line in the figure shows the minimum level at which a weak signal can be detected. According to this figure, a weak signal coexists with a -13 dB strong signal has a minimum detectable signal power level of -30 dB. If a weak signal coexists with a -19 dB signal, then the minimum detectable level is about -34.5 dB.

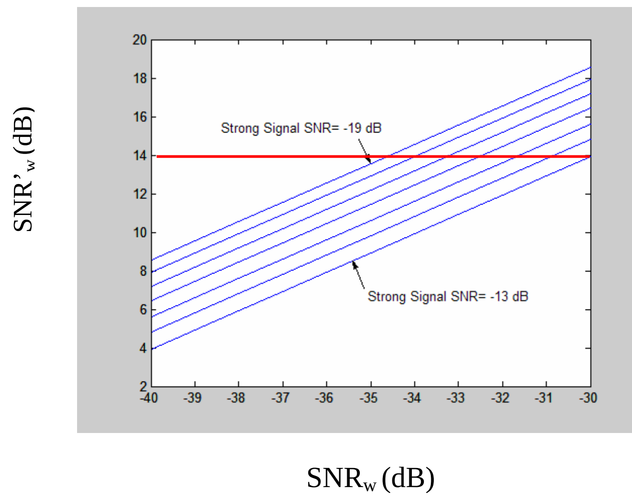

Fig. 2. Processed weak signal to noise ratio as a function of input weak signal to noise ratio and the strong signal to noise ratio.

Based on the above analysis, it is evident that in order to successfully acquire weak signals at the sensitivity limit level, it is necessary to remove the nominal signals. The following section discusses an algorithm developed to achieve this purpose.

3. STRONG SIGNAL RECONSTRUCTION USING SUBSPACE PROJECTION METHOD

Two approaches, direct reconstruction and projection method, were used for strong signal cancellation. Both approaches utilize Doppler frequency, CA code offset, and carrier phase results for strong satellites obtained from a tracking program. In the direct reconstruction method, the signal to noise ratio information obtained from the tracking program is used to calculate the strong signal amplitude. This amplitude value, combined with the other parameters from the tracking loop, were used to directly reconstruct the strong signal. The projection

method treats the strong signals as a subspace of the total GPS input signal space. The Doppler frequency, CA code offset, and the carrier phase information obtained from the tracking program are used to form the subspace. Projections of the input signal onto the strong signal subspace represents the total strong signal contribution to the input signal. We compared the performance of the two approaches and found that the projection method outperforms the direct reconstruction method by producing smaller residue errors under all conditions. Therefore, we will only focus our study here on the projection method.

The projection method is based on the work of Behrens and Scharf (1996), and Scharf and Friedlander (1994). In their work, the collection of interference signals is treated as a subspace of the input signals. Column vectors are used to represent interference signals, and a matrix composed of these column vectors is used to represent a space spanned by the interference signals. In our case, the goal is to remove the strong satellite signals from the GPS input and to acquire weak satellite signals. Therefore, we will treat the strong signals as interference. Based on the vector space notion, the down converted GPS input samples can be represented as a vector **y**:

$$\boldsymbol{y} = \boldsymbol{a_W H} + \boldsymbol{a_S S} + \boldsymbol{n} \qquad (10)$$

Where,

$\boldsymbol{y}=[y(0),\ y(1),\ y(2),\ldots,y(N-1)]^T$, N is the number of samples in the input data.

H: A matrix whose columns are unit vectors containing samples of down-converted weak signals.

$\boldsymbol{a_w}$**:** Amplitude vector for the weak signals**.**

S: A matrix whose columns are unit vectors containing samples of down-converted strong signals.

$\boldsymbol{a_s}$**:** Amplitude vector for the strong signals.

n: Noise vector whose mean and variance (σ^2) are known.

Figure 3 shows the schematic of the signal ***y*** in term of its vector space representation. The projection of the input signal y onto the **<*HS*>** subspace is denoted as $\boldsymbol{P_{HS}y}$

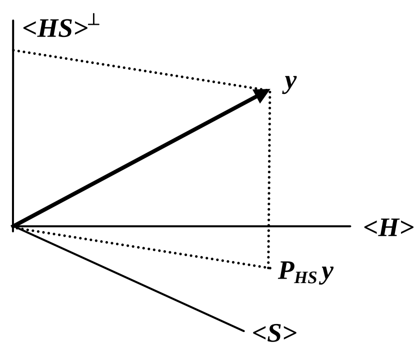

Fig.3. GPS Input Signal ***y*** in vector space representation

The projection $\boldsymbol{P_{HS}\,y}$ can be further decomposed into two components: the projection onto the <***S***> space $\boldsymbol{P_S\,y}$, and the projection on the <$\boldsymbol{P_S^{\perp}H}$> subspace. Figure 4 shows the schematics of this projection. The component of interests here is the one onto the strong signal subspace, $\boldsymbol{P_S\,y}$:

$$\boldsymbol{P_s\,y} = \boldsymbol{S}(\boldsymbol{S}^{\mathbf{T}}\boldsymbol{S})^{-1}\boldsymbol{S}^{\mathbf{T}}\,\boldsymbol{y} \qquad (11)$$

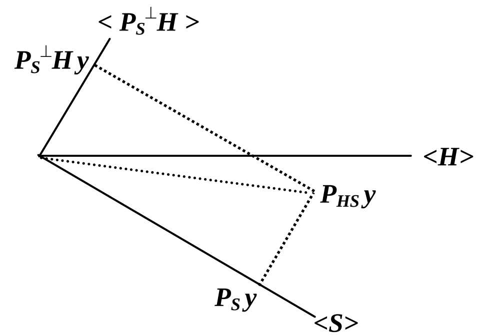

Fig.4. GPS input signal ***y*** projections onto strong signal subspaces

Since the GPS satellite signals uses codes that are nearly orthogonal to each other,

$$\boldsymbol{S}^{\mathbf{T}}.\boldsymbol{H} \cong \boldsymbol{0} \qquad (12)$$

Therefore,

$$\begin{aligned}\boldsymbol{P_s\,y} &= \boldsymbol{S}(\boldsymbol{S}^{\mathbf{T}}\boldsymbol{S})^{-1}\boldsymbol{S}^{\mathbf{T}}\,\boldsymbol{y}\\ &= \boldsymbol{S}(\boldsymbol{S}^{\mathbf{T}}\boldsymbol{S})^{-1}\boldsymbol{S}^{\mathbf{T}}\,(\boldsymbol{a_w H}+\boldsymbol{a_n S}+\boldsymbol{n})\\ &= \boldsymbol{a_n S}+\boldsymbol{P_s\,n} \qquad (13)\end{aligned}$$

Equation (13) indicates that if we have acquired knowledge of all the strong satellite signals, we can construct the strong signal subspace matrix ***S***, the projection of the input signal ***y*** onto the subspace <***S***> is the sum of the strong satellite signals and the projection of the noise onto the subspace <***S***>. If we use the projection $\boldsymbol{P_s\,y}$ as an estimate of the strong signal contribution to the GPS receiver input, the residue of such an estimate is the projection of the noise onto the subspace <***S***>.

If we can acquire and track all strong satellite signals to obtain the necessary parameters (Doppler frequency, CA code offset, and carrier phase) to construct the ***S*** matrix:

$\mathbf{S}=[S_1, S_2,\ldots, S_{i,\ldots}]$

Where, the *ith* column vector S_i represents the digitized samples of satellite i's input:

$$S_i(t) = C_i(t, p\hat{t}_i)\sin(2\pi\hat{f}_{di} + \hat{\phi}_i) \qquad (14)$$

C_i is satellite i's C/A code with offset $p\hat{t}_i$. $\hat{f}_{di}$ and $\hat{\phi}_i$ are the Doppler shift frequency and carrier phase obtained from the tracking program. Using equation (11), we can calculate the projection of a GPS input signal onto the <***S***> subspace. This projection can be used as an

estimation of strong signal contributions to the input signal. Subtracting this estimation from the input results in a net signal consisting of weak signal, noise, as well as residue error resulted from the projection.

The weak signal acquisition algorithm used in this project (to be discussed in detail in the next section) uses up to 200 ms of data. For such extended time duration, even a minor change in the Doppler frequency will result in sizable error in the carrier phase estimation. For example, a 0.1Hz shift in Doppler frequency will cause a phase shift of $2\pi\times0.2\times0.1=12^{o}$ after 200 ms. An offset of such magnitude will introduce considerable error in strong signal reconstruction and cancellation. To overcome this problem, we divided the input signal into blocks of 10 ms length. Doppler frequency, CA code offset, and carrier phase were obtained for each of the 10 ms blocks. The ***S*** matrix was created for each 10 ms data block. Projection of the input signal on to the ***S*** space was also performed every 10 ms. The strong signal projections from up to 20 blocks of data were combined to form a 200 ms projection. The difference between the original 200 ms of data the combined 200 ms projection is then used for weak signal acquisition.

4. WEAK SIGNAL ACQUISITION ALGORITHM

To acquire weak signal at the sensitivity level, a combination of coherent integration and incoherent integration method was used. Tsui (to be published) has a detailed description of the algorithm. The general methodology is provided here for the purpose of completeness.

Data blocks of 10 ms in length were used in the FFT-based coherent integration procedure as described in Tsui (2000). This coherent integration leads to a processing gain of 33 dB. The length of 10 ms is chosen because of the existence of navigation data bits in the input. A navigation data bit transition may occur once every 20 ms. When there are phase transitions caused by navigation data bits, the coherent integration procedure will no longer produce the desired gain. In two consecutive 10 ms of data blocks, one is guaranteed to not contain a phase transition. One may divide 400 ms of data into 40 blocks, each lasts 10 ms. The block number 1, 3, 5, …., 19 and the block 2, 4, 6, ..., 20 can be used to form two separate sequences and treated separately in incoherent integration process. One of the sequences will not contain navigation data transition.

As mentioned earlier, to acquire a weak signal at the sensitivity limit level, a total of 53 dB processing gain is need. Since 10 ms of coherent integration can only provide 33 dB processing gain, incoherent integration will be used to provide the additional 20 dB gain.

The incoherent gain G_i can be computed from this formula (Barton, 1988)

$$G_i = 10\log(m) - L(m) \quad dB \tag{14}$$

Where, m is the number of incoherent integration performed, and $L(m)$ is the so-called incoherent integration loss. Lin et al. (2002) provided details on the computation of $L(m)$ and G_i the result is reproduced in Fig. 5 for reference.

According to Fig. 5, to obtain 10 dB processing gain from incoherent processing, 19 incoherent integrations is needed. As a result, a total of 190 ms of data is needed to acquire a weak signal at the sensitivity limit. Taken into consideration of initial code shifts, etc., we usually take 200 ms of data for the weak signal acquisition. To take care of navigation data bits change, a total of 400 ms of input data will be used. But only half of the 400 ms will be used to generate acquisition results.

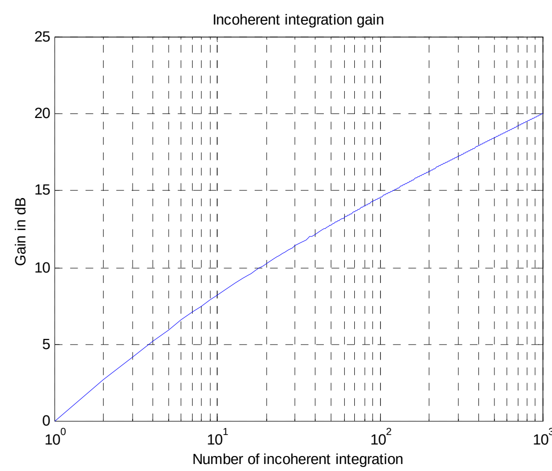

Fig. 5. Incoherent integration gain as a function of the number of integration.

5. TESTING RESULTS AND CONCLUSIONS

Both simulation and simulator data were used to test the strong signal cancellation algorithm discussed in Section 3 and the weak signal acquisition algorithm discussed in Section 4. Based on our testing results, we can arrive at the following conclusions:

(1). In the absence of any strong signal, the lowest input SNR can be acquired is -39 dB (C/N_0=24 dB-Hz).

(2). In the presence of a strong signal, the lowest weak signal can be acquired depends on the strong signal level, if strong signal is not removed. Table 1 shows several sets of test results.

(3). If a strong signal with input SNR=-13 dB is removed using the projection method, the lowest weak signal can be acquired has SNR=-39 dB (C/N_0=24 dB-Hz). Upto 3 strong satellite signals with were tested in simulation study. The algorithm presented in the paper was able to

cancel all three strong satellite signals and successfully acquire a weak satellite signal with C/N_0=24 dB-Hz.

Table 1. Lowest weak signal level can be acquired without strong signal cancellation based on simulation.

Lowest weak signal input SNR can be acquired	Strong signal input SNR
-32 dB (C/N_0=31 dB-Hz)	-13 dB (C/N_0=50 dB-Hz)
-33 dB (C/N_0=30 dB-Hz)	-15 dB (C/N_0=48 dB-Hz)
-35 dB (C/N_0=28 dB-Hz)	-17 dB (C/N_0=46 dB-Hz)

Figure 6 shows an example weak signal time domain correlation plot generated for a set of hardware-based simulator data. The data contains two GPS signals: satellite #7 and satellite #11. The input signal to noise ratio of the two satellites are -13 dB and -39 dB respectively. The strong signal cancellation method was applied to the input data and satellite #7. Satellite #11 was then acquired using the method described in Section 4.

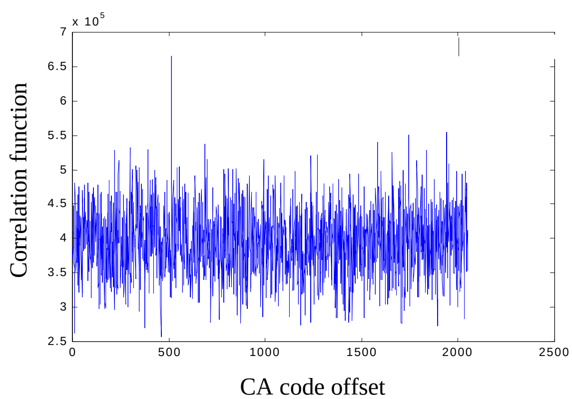

Figure 6. Correlation function for a weak satellite signal with SNR=-39 dB. The weak signal coexisted with a strong signal with SNR=-13 dB.

Our testing results show that the projection method can effectively remove the strong signal, and hence, the CA code interference between the strong and the weak signals. Our simulation test also shows that the interference removal procedure is not effective if the strong and weak satellite signal Doppler frequencies are very close. This may be due to the fact that when two signals Doppler shift are very different, the carrier of the two signals can be considered as orthogonal signals. Since the residue error generated by the projection operation is the dot product between the strong signal subspace matrix and the weak signal subspace matrix, the additional orthogonality helped to maintain minimum residue error. When the Doppler frequencies are close, the carrier orthogonality advantage disappears. Since the CA codes are only "near" orthogonal, and since the cross correlation of the CA code are not exactly "random" in nature, the projection method may leave enough residue error to prevent successful acquisition of the weak signals.

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REFERENCES

1. Van Dierendonck, A. J., McGraw, G. A., Erlandson, R. J., and Coker, R. S., "Cross-correlation of C/A Codes in GPS/WAAS Receivers,", Proceedings of ION GPS-99, Nashville, TN, Sept. 14-17, 1999, pp. 582-590.
2. Van Dierendonck, A. J., Erlandson, R. J., and Coker, R. S., "Determination of C/A Code Self-Interference Using Cross-Correlation Simulations and Receiver Bench Tests", Proceedings of ION GPS-2002, Portland, OR, Sept. 24-27, 2002, pp. 630-642.
3. Van Dierendonck, A. J., "GPS receivers," in Global Positioning System: theory and Applications, Vol. I, Parkingson, B. W. and Spilker, J. J. Jr., eds., American Institute of Aeronautics and Astronautics, pp329-407, Washington, 1996.
4. Ward, P. W., "Satellite signal acquisition and tracking," in Understanding GPS, Principles and Applications, Kaplan, E. D. editor, Artech House Publisher, pp.119-228, 1996.
5. Tsui, J. B. Y., "Fundamentals of Global Positioning System Receivers, A Software Approach", Chapter 10, John Wiley & Son, Inc., 1st edition, pp133-159, 2000.
6. Lin, D.M., Tsui, J., "Comparison of acquisition methods for software GPS receiver, " ION GPS 2000 pp. 2385-2389, Salt Lake City, UT, Sept., 2000.
7. Akos, D. M., Normark, P., Lee, J., Gromov, K. G., Tsui, J. B. Y., and Schamus, J., "Low power global navigation satellite systems (GNSS) signal detection and processing", Proc. Of ION GPS-2000, Salt Lake City, UT, Sept. 19-22, 2000, pp784-791.
8. Psiaki, M. L>, "Block acquisition of weak GPS signals in a software receiver," Proc. Of ION GPS-2001, Salt Lake City, UT, Sept. 11-14, 2001, pp2838-2850.
9. Hallen, A., et al., "Multi-user detection in CDMA systems," IEEE Personal Communications, Apr. 1995, pp46-58.

10. Madhani, P. H., Axelrad, P., Krumvieda, K., and Thomas, J., "Application of successive interference cancellation to the GPS pseudolite near-far problem,", IEEE Trans. On Aerospace and Electroni systems, V. 39, No. 2, April 2003.
11. Tsui, J. B. Y., "Fundamentals of Global Positioning System Receivers, A Software Approach", Chapter 10, John Wiley & Son, Inc., 2nd edition, to be published.
12. Van Dierendonck, A. J., McGraw, G. A., Erlandson, R. J., and Coker, R. S., "Cross-correlation of C/A Codes in GPS/WAAS Receivers,", Proc. of ION GPS-99, Nashville, TN, Sept., 1999, pp. 582-590.
13. Van Dierendonck, A. J., Erlandson, R. J., and Coker, R. S., "Determination of C/A Code Self-Interference Using Cross-Correlation Simulations and Receiver Bench Tests", Proceedings of ION GPS-2002, Portland, OR, Sept., 2002, pp. 630-642.
14. Barton, D.K., "Modern radar system analysis," Artech House, Norwood, MA., 1988.
15. Behrens, R. T., and Scharf, L. L., "Signal Processing Applications of Oblique Projection Operators", *IEEE Transactions on Signal Processing*, Vol.42, No. 6, p1413-1423, June 1994.
16. Scharf, L. L., and Friedlander, B., "Matched Subspace Detectors", *IEEE Transactions on Signal Processing*, Vol. 42, No.8, p2146-2157, August, 1994.
17. Lin, D. M., Tsui, J. B. Y., Liou, L., and Morton, Y. T., "Sensitivity limit of a stand-alone GPS receiver", Proceedings of 2002 ION GPS conference, Portland, Oregon, Sept. 2002.